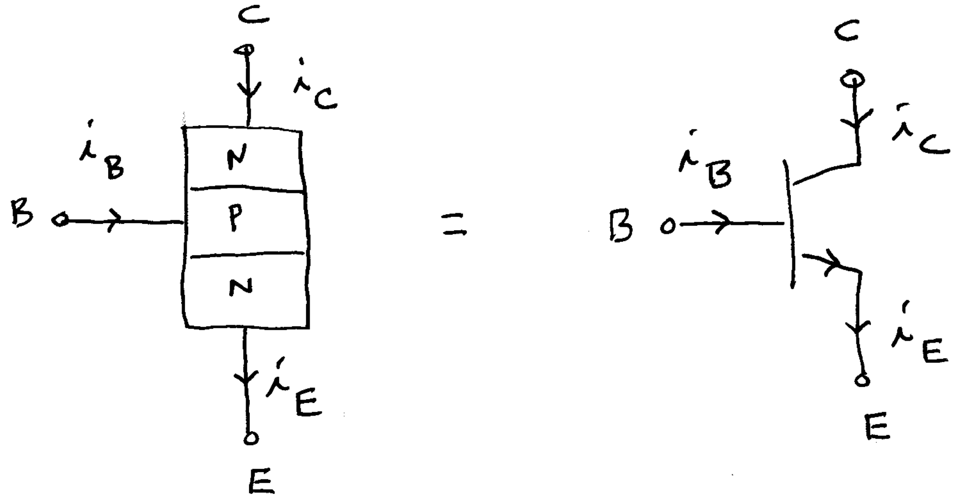
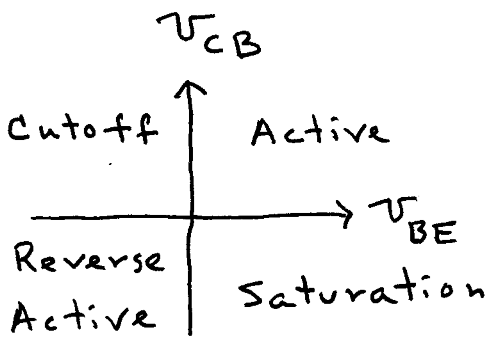
The BJT - NPN Device



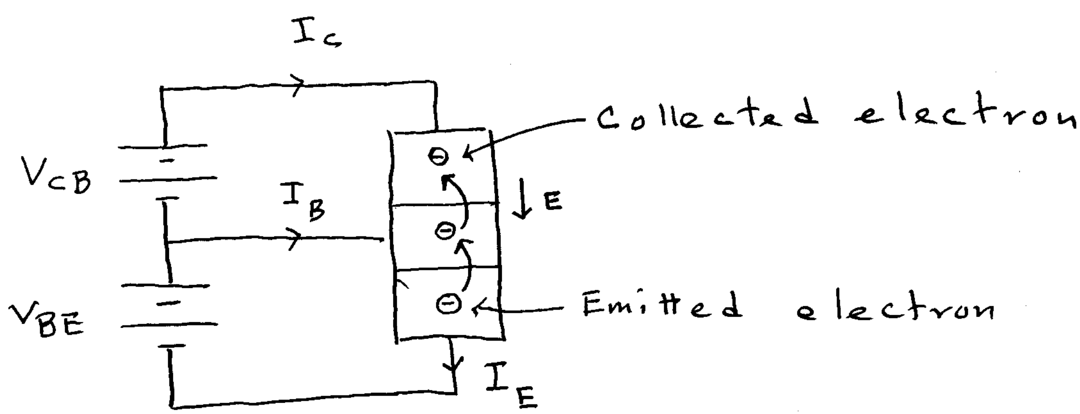
Modes of operation



In the active mode, the B-E junction is forward biased. The C-B junction is reverse biased. The labeled current directions are for the active mode. For the PNP device, the current directions are reversed.

In the NPN device, the p type impurity doping in the base is very small compared to the n type impurity doping in the collector and emitter. For this reason, electrons are the majority current carriers. In the PNP device, holes are the majority current carriers.

NPN BJT in the Active Mode



Electrons are emitted from the emitter region across the forward biased B-E junction into the base region. The E field across the reversed biased CB junction attracts these electrons and they are collected by the collector. The fraction of collected electrons is denoted by α. Thus we have

$$I_C = \alpha I_E$$

$$I_B = I_E - I_c = (1-\alpha) I_E$$

$$\Rightarrow \quad I_E = \frac{1}{1-\alpha} I_B$$

$$\Rightarrow \quad I_c = \frac{\alpha}{1-\alpha} I_B$$

The current gain β is defined by

$$\beta = \frac{\alpha}{1-\alpha}$$

$$\Rightarrow \quad I_c = \beta I_B = \alpha I_E$$

In general, we can write

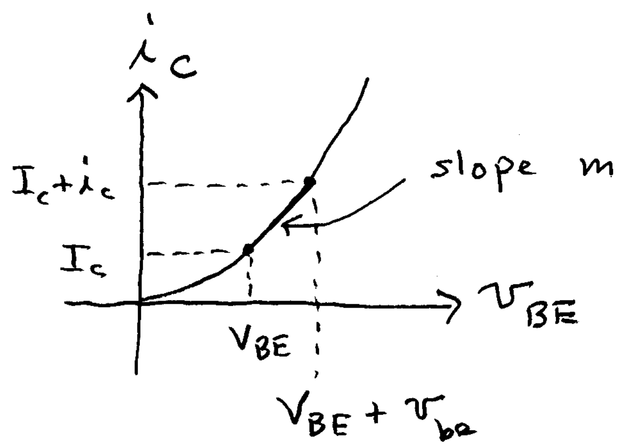
$$i_C = \beta i_B = \alpha i_E$$

The Transfer Characteristics

These are plots of i_C versus v_{BE} for v_{CE} = constant

$$i_C = I_S e^{v_{BE}/V_T}$$

where $I_S = I_{S0}\left(1 + \frac{v_{CE}}{V_T}\right)$ = constant



Draw a tangent line at the point (V_{BE}, I_C). The slope of the line can be used to relate changes in i_C to changes in v_{BE}.

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$$m = \frac{\partial I_C}{\partial V_{BE}} = I_S \, e^{V_{BE}/V_T} \times \frac{1}{V_T}$$

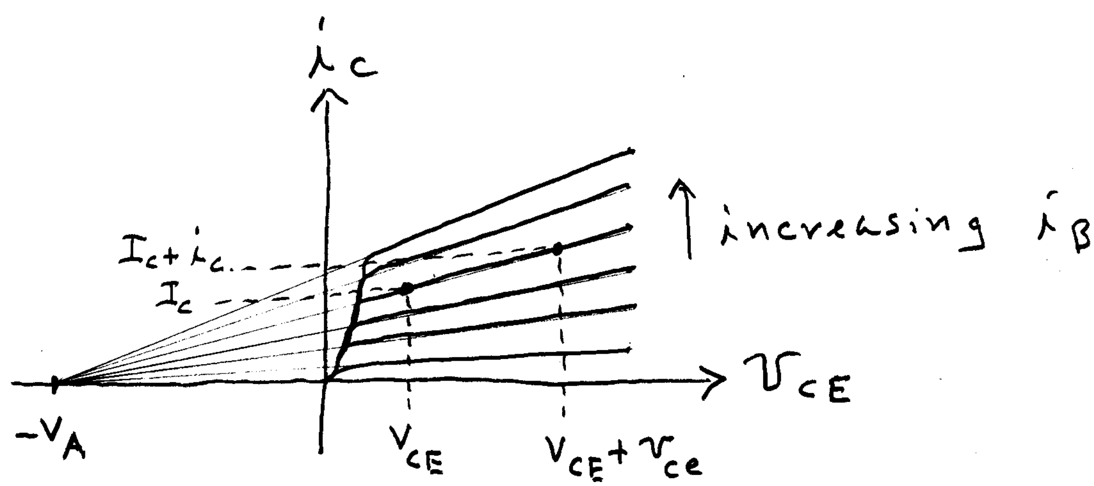
$$= \frac{I_C}{V_T}$$

$$\Rightarrow i_c = \frac{I_C}{V_T} v_{be}$$

The output Characteristics

These are plots of i_C versus v_{CE} for i_B = constant.

$$i_C = \beta \, i_B = \beta_o \left(1 + \frac{v_{CE}}{V_A}\right) i_B$$



Draw a tangent line at the point (V_{CE}, I_C). The slope of the line can be used to relate changes in i_C to changes in v_{CE}.

$$m = \frac{\partial I_C}{\partial V_{CE}} = \beta_o \frac{1}{V_A} I_B$$

$$= \beta_o \frac{1}{V_A} \frac{I_C}{\beta}$$

$$= \frac{\beta_o}{V_A} \frac{I_C}{\beta_o \left(1 + \frac{V_{CE}}{V_A}\right)}$$

$$= \frac{I_C}{V_A + V_{CE}}$$

$$\Rightarrow \quad i_c = \frac{I_C}{V_A + V_{CE}} v_{ce}$$

Thus, in general, we have

$$i_c = \frac{I_C}{V_T} v_{be} + \frac{I_C}{V_A + V_{CE}} v_{ce}$$

Let us define

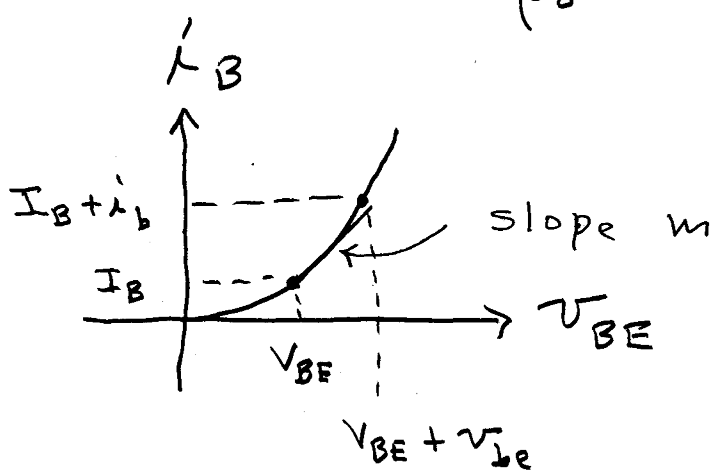
$$g_m = \frac{I_C}{V_T} \qquad r_o = \frac{V_A + V_{CE}}{I_C}$$

$$\Rightarrow \quad i_c = g_m v_{be} + \frac{v_{ce}}{r_o}$$

Next, we relate the change in i_B to a change in v_{BE}.

$$i_B = \frac{i_C}{\beta} = \frac{I_{SO}\left(1 + \frac{v_{CE}}{V_A}\right) e^{v_{BE}/V_T}}{\beta_o\left(1 + \frac{v_{CE}}{V_A}\right)}$$

$$= \frac{I_{SO}}{\beta_o} e^{v_{BE}/V_T}$$



Draw a tangent line at the point (V_{BE}, I_B). The slope of the line can be used to relate changes in i_B to changes in v_{BE}.

$$m = \frac{dI_B}{dV_{BE}} = I_{so}\, e^{V_{BE}/V_T} \times \frac{1}{V_T}$$

$$= \frac{I_B}{V_T}$$

$$\Rightarrow \quad i_b = \frac{I_B}{V_T}\, v_{be}$$

Let us define $r_\pi = \dfrac{V_T}{I_B}$

$$\Rightarrow \quad i_b = \frac{v_{be}}{r_\pi}$$

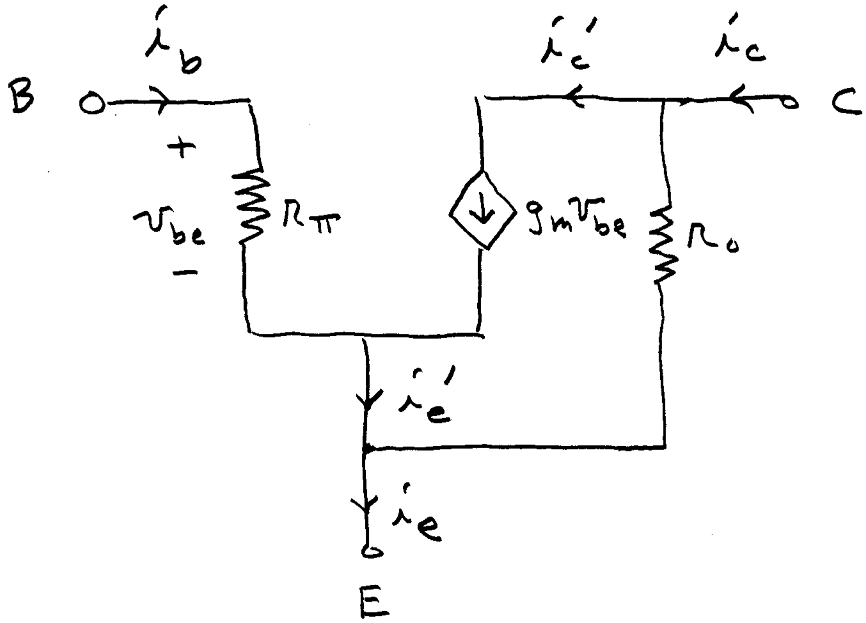
The Hybrid-π Model

The basic equations are

$$i_c = g_m v_{be} + \frac{v_{ce}}{r_o}$$

$$i_b = \frac{v_{be}}{r_\pi}$$

We can draw the model as follows:



We seek the relationships between i_c', i_b, and i_e'.

$$i_c' = g_m v_{be} = g_m(i_b R_\pi)$$

$$= g_m R_\pi i_b = \frac{I_C}{V_T}\frac{V_T}{I_B} i_b$$

$$= \frac{I_C}{I_b} i_b = \beta i_b$$

$$i_e' = i_c' + i_b = i_c' + \frac{1}{\beta} i_c'$$

$$= i_c'\left(1 + \frac{1}{\beta}\right) = i_c' \frac{1+\beta}{\beta}$$

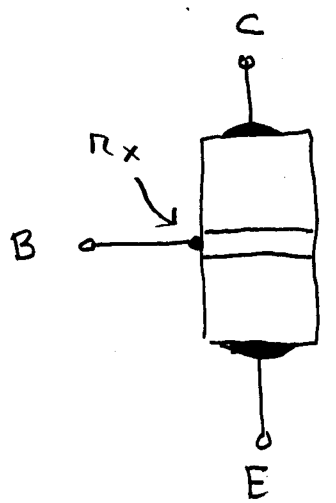
$$= \frac{i_c'}{\alpha}$$

Thus we have

$$i_c' = g_m v_{be} = \beta i_b = \alpha i_e'$$

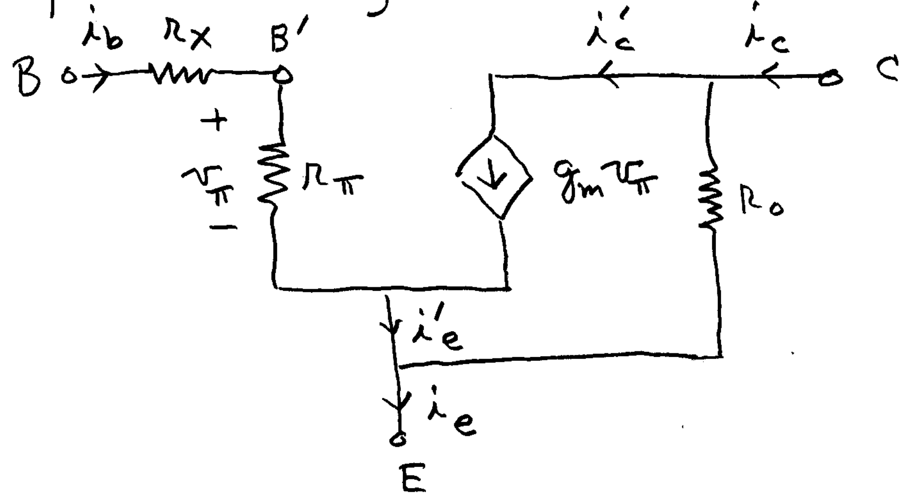
If $r_o = \infty$ (open circuit), the primes can be dropped.

The Base Spreading Resistance



The base region is narrow and its ohmic contact is small. Its resistance is denoted by r_x.

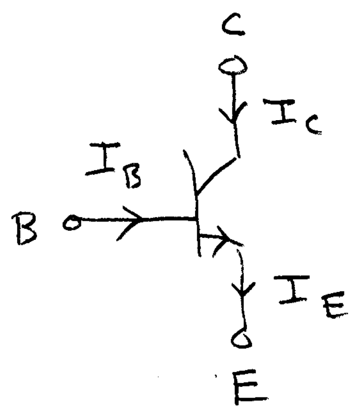
Completed Hybrid - π Model



In this case, we write

$$i_c' = g_m v_\pi = \beta i_b = \alpha i_e'$$

DC Current Relations



$$I_B = \frac{I_c}{\beta}$$

$$I_E = I_B + I_c$$

$$= I_c \left(\frac{1}{\beta} + 1 \right)$$

$$= I_c \frac{1+\beta}{\beta}$$

$$= \frac{I_c}{\alpha}$$

$$\Rightarrow \quad I_c = \beta I_B = \alpha I_E$$

$$I_B = I_E - I_c = I_E - \alpha I_E$$

$$= I_E (1-\alpha) = I_E \left(1 - \frac{\beta}{1+\beta} \right)$$

$$= \frac{I_E}{1+\beta}$$

Summary

$$I_C = \beta I_B = \alpha I_E$$

$$I_E = \frac{I_C}{\alpha} = (1+\beta) I_B$$

$$I_B = \frac{I_C}{\beta} = \frac{I_E}{1+\beta}$$

$$\alpha = \frac{\beta}{1+\beta} \qquad \beta = \frac{\alpha}{1-\alpha}$$

The BJT T Model

The T model replaces r_π through which i_b flows with r_e through which i_e' flows. The voltage v_π must be the same for the two.

$$v_\pi = i_b r_\pi = \frac{i_c'}{\beta} r_\pi = \frac{\alpha i_e'}{\beta} r_\pi$$

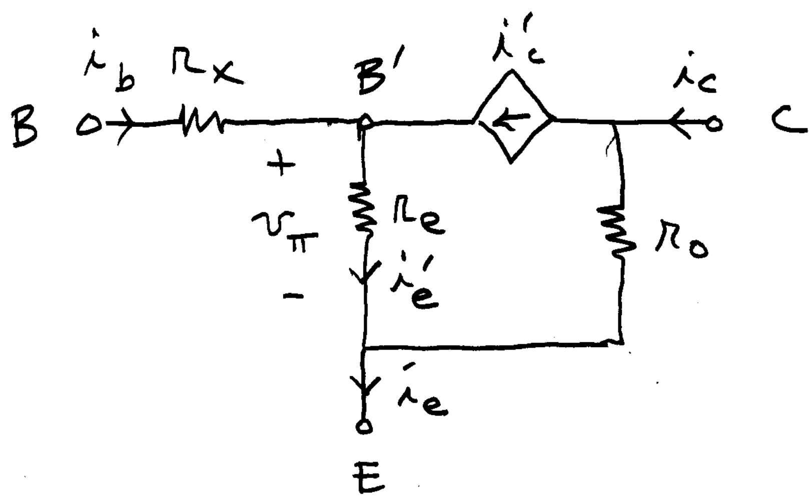
$$= i_e' \frac{\alpha}{\beta} r_\pi = i_e' \frac{\alpha}{\beta} \frac{V_T}{I_B} = i_e' \frac{\alpha V_T}{I_C}$$

$$= i_e' \frac{V_T}{I_E}$$

Let $r_e = \frac{V_T}{I_E}$

$\Rightarrow \quad v_\pi = i_e' \, r_e$

The resistor r_e is called the intrinsic emitter resistance.
The T model is



$$i_c' = g_m v_\pi = \beta i_b = \alpha i_e'$$

Both the T model and the hybrid-π models give identical answers when numbers are substituted into the equations.